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Stennis Space Center, MS 39529-5004

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Tidal Atlas Software Development

Y. LARRY HSU

*Mapping, Charting, and Geodesy Branch
Marine Geosciences Division*

JUAN F. REYNAUD

*Mississippi Research Center
Mississippi State University
Stennis Space Center, MS 39529*

ERNST W. SCHWIDERSKI

*102 Bell Street
Fredericksburg, VA 22405*

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13. Abstract (Maximum 200 words). Tidal atlas software has been developed for naval hydrographic survey operations. The software displays an integrated database of tides, bathymetry, and coastlines. It is a menu-driven PC/WINDOWS program. The tidal databases include the tidal constituent bank from the International Hydrographic Organization and Schwiderski's global tidal data. The bathymetry uses the 5-minute ETOPO5 database and the coastlines use the world vector shoreline database. The software can display tidal stations and tidal constituents for a user-specified area. The software also provides other functions including tidal height plot, tidal zone plot, cotidal, and corange plots. The software is available only upon request to the Naval Research Laboratory, Code 7442, Stennis Space Center, MS 39529-5004. It is not included with this report unless requested.					
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I. Introduction

The tidal atlas software (TAS) was developed for the Hydrographic Department of the U.S. Naval Oceanographic Office (NAVOCEANO) to retrieve and display global tidal characteristics. The software can display an integrated database including tides, coastlines, and bathymetry. The tidal databases include the International Hydrographic Organization (IHO) tidal constituent bank (Anonymous 1988) consisting of 4,500 stations and Schwiderski's global ocean tide (GOT) data at 1° resolution (Schwiderski and Szeto 1981). The GOT data consists of eight (M_2 , S_2 , K_1 , O_1 , N_2 , P_1 , K_2 , and Q_1) major components and three long period components (M_f , M_m , and S_{sa}). The bathymetry uses the 5-minute ETOPO5 database and the coastlines use the world vector shoreline (WVS) database.

Using TAS, one can quickly examine the tidal characteristics for a selected region. The major display features include tidal data display, cotidal and corange plots, tidal height plot, and tidal zone plot.

II. General Description of the Software

The main flow diagram of TAS is shown in Fig. 1. Basically, its functions consist of data retrieving, data display and editing, gridding, and generating output files and plots. Most of the data retrieving and processing routines are written in FORTRAN and C languages. The user-friendly features and the display graphics are based on the Visual Basic for Windows. The functions of TAS are completely menu-driven. All initial program setup and user input are entered through dialogue boxes. A hard copy of any graphic display can be produced by using the device drivers in the Windows software.

To produce cotidal, corange and tidal zone plots, the combined IHO and Schwiderski data are gridded. A gridding program, CHTRT provided by NAVOCEANO is used for gridding. It applies a minimum curvature scheme to produce a regional grid (Swain 1976). The final grid is then derived by merging it with the actual data points using a cubic spline.

III. Main Display Features

Main display features are described in this section. Additional features are presented in the Users Manual (see Appendix A).

1. Tidal Data Display

The full content of the IHO and Schwiderski data can be displayed as shown in Fig. 2. For a selected area, the tidal amplitude and phase for eight major constituents can be displayed under the station mark as shown in Fig. 3. The IHO phase data can be retrieved either for the local or Greenwich time frame. The original IHO data are listed in the local time frame. The

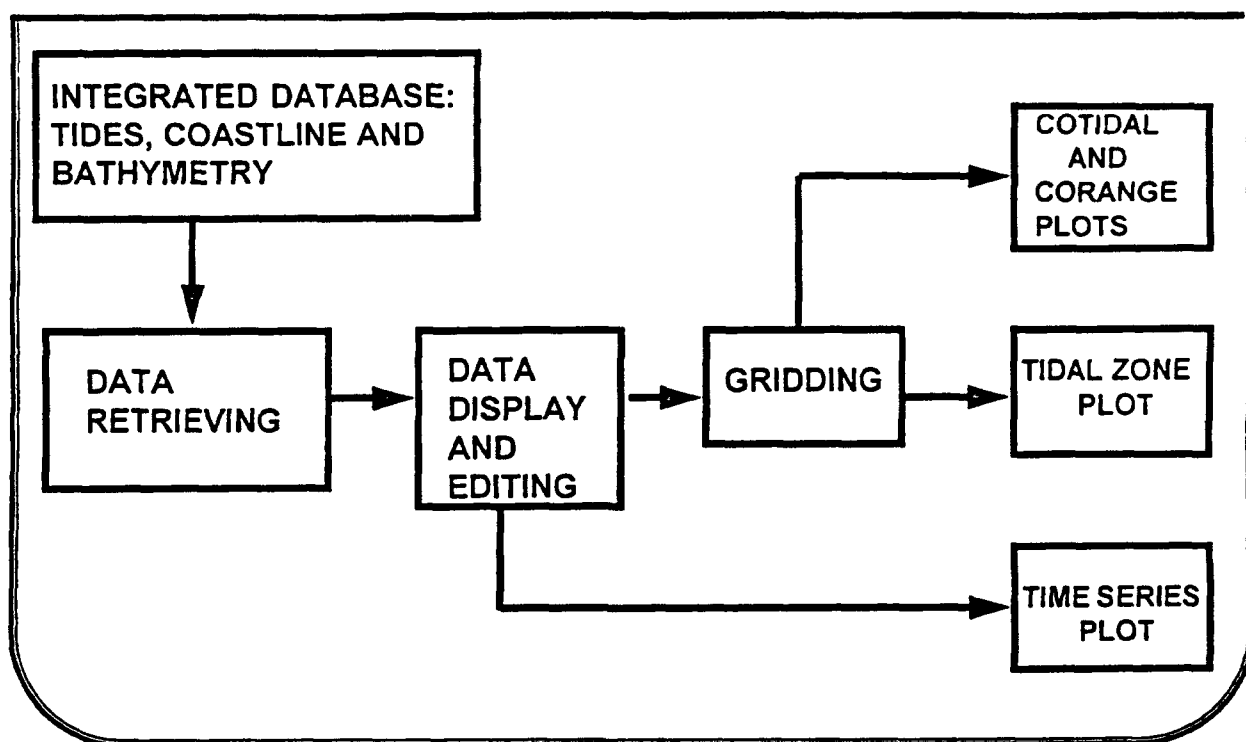


Fig. 1. Main Flow Diagram of the Software

IHO Information

IHO Station Name: **SANTA MONICA**

Station Coordinates: 34 N 118.5 W

Number of Constituents: 9

Time Zone: 8 Mean Water Level: .9

Constituent	Amplitude	Phase
K1	.341	208.5
O1	.215	194.5
P1	.11	205.5
Q1	.039	188.5
M2	.505	148
S2	.195	142
N2	.118	125
K2	.051	140

Ok

Print

Print Raw Data

Fig. 2. Sample IHO Tidal Constituents at Santa Monica

conversion formula is

$$G = g + S * \text{Time Zone}$$

where G is Greenwich phase, g is local phase and S denotes constituent speed in unit of (degree/hour). Time Zone is the time reference used in the tidal analysis, for example, the time zone is 4 hours for the Mississippi coast.

2. Cotidal and Corange Plots

After gridding, the cotidal and corange plots can be produced. A dialogue box requests user inputs for contouring parameters such as contour interval. By refreshing the display, the contours can be plotted again using different contouring parameters. The M2 cotidal and corange plots for the California coast are shown in Figs. 3 and 4.

3. Tidal Height Plot

The tidal height plot can be produced for any IHO or GOT station. The prediction software was developed by Foreman (1977). An example of a tidal curve for Santa Monica, California, is shown in Fig. 5.

4. Tidal Zone Plot

A common way to characterize the tidal type of a region is using the form number F (Dietrich 1967),

$$F = (K1+O1) / (M2+S2)$$

F: 0-0.25 semidiurnal tide

F: 0.25-3.0 mixed tide

F: >3.0 diurnal tide.

A sample tidal zone plot for the west Florida coast is shown in Fig 6. Diurnal tides are usually dominant in the Gulf of Mexico. The resonance of the semidiurnal M2 tide on the shelf makes the eastern part of this region an exception.

5. Data Flag for GOT Data

Schwiderski identified areas where additional measurement or modeling is needed for GOT data. Two files are created based on his report (see Appendix B). A message is displayed if the selected coordinates fall in the identified areas. An example for the Argentina coast is illustrated in Fig. 7. In this case, the GOT data is not accurate due to large river outflow and shallow banks.

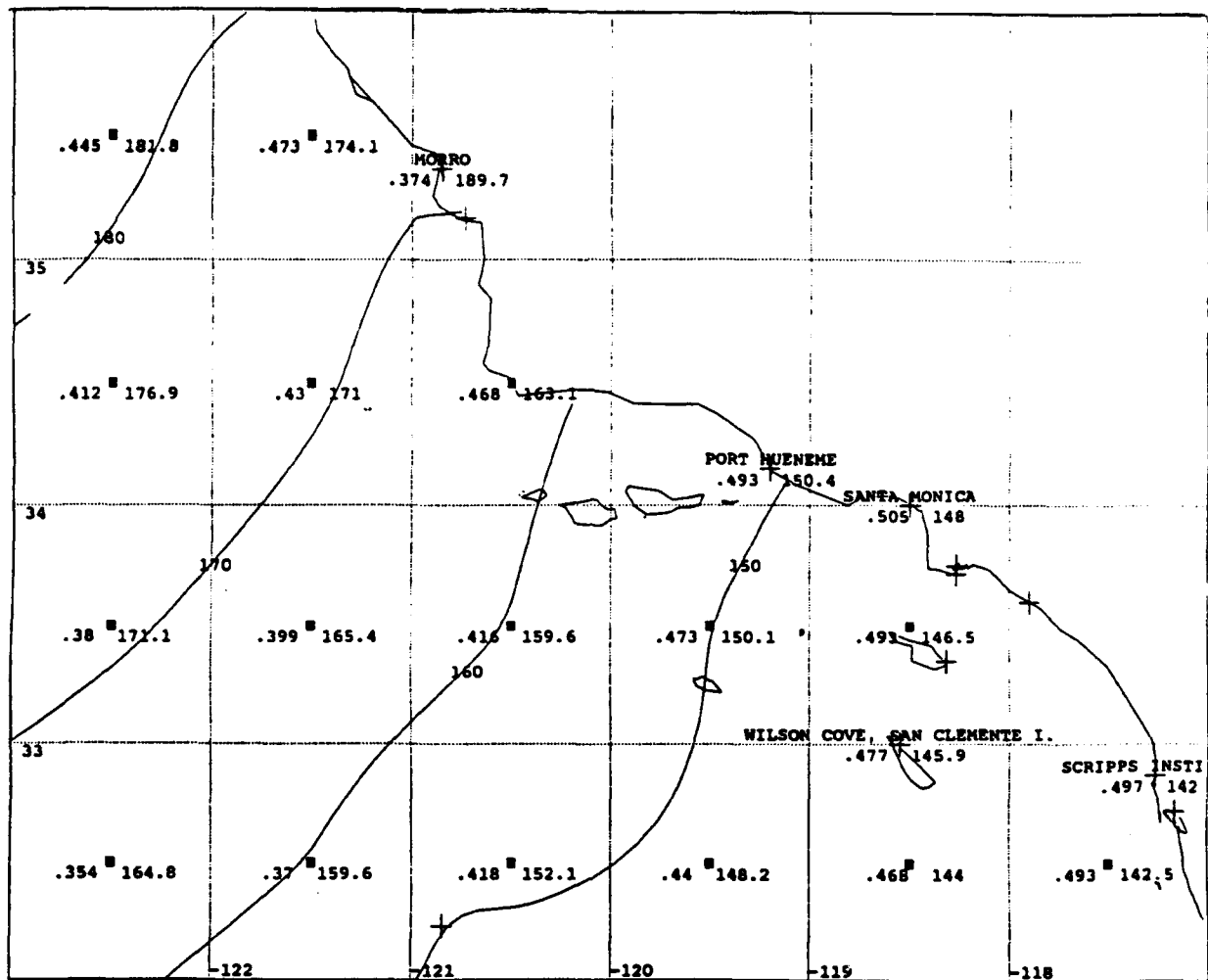


Fig. 3. M2 Cotidal (Degree in Greenwich) Plot of California

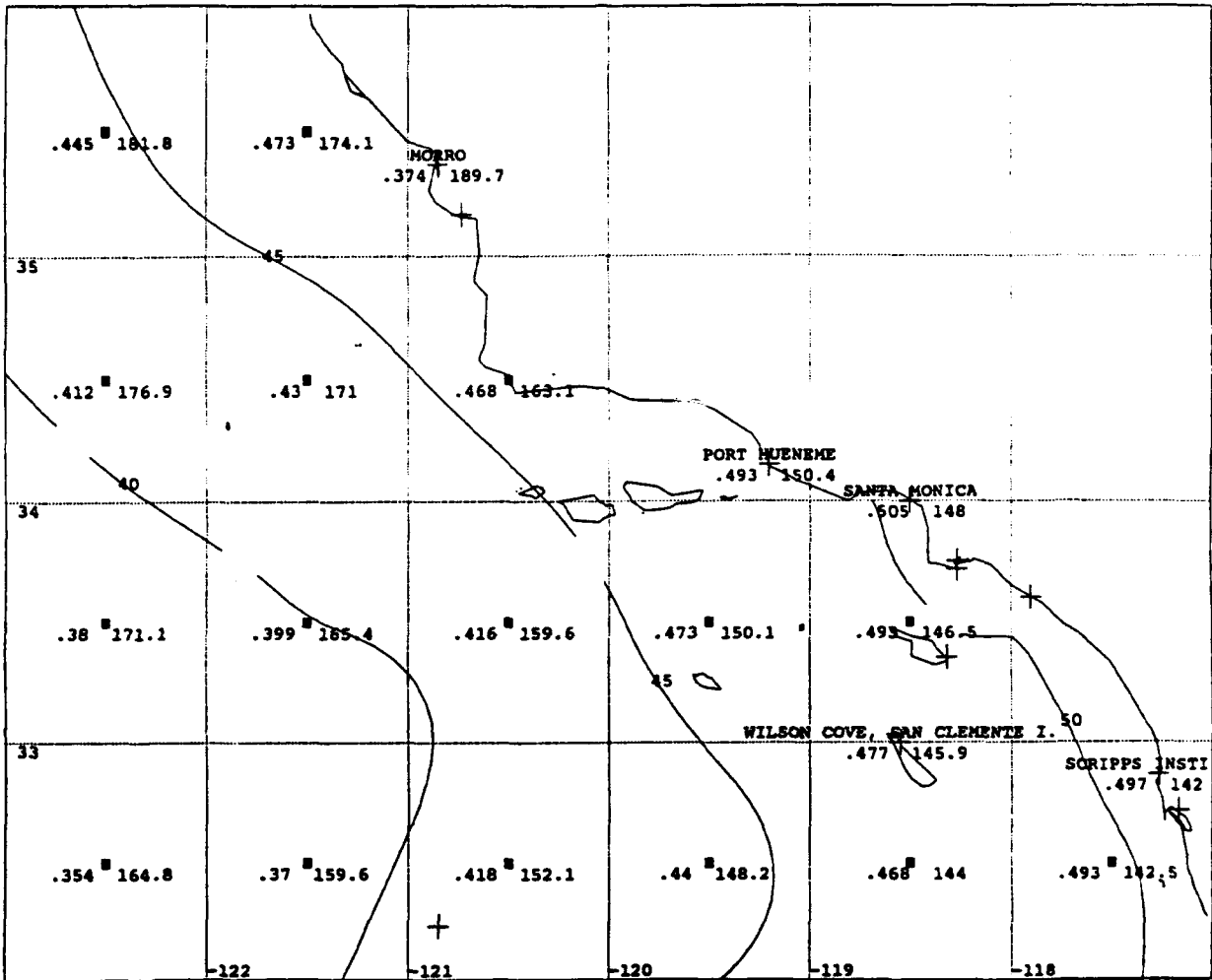


Fig. 4. M2 Corange (cm) Plot of California

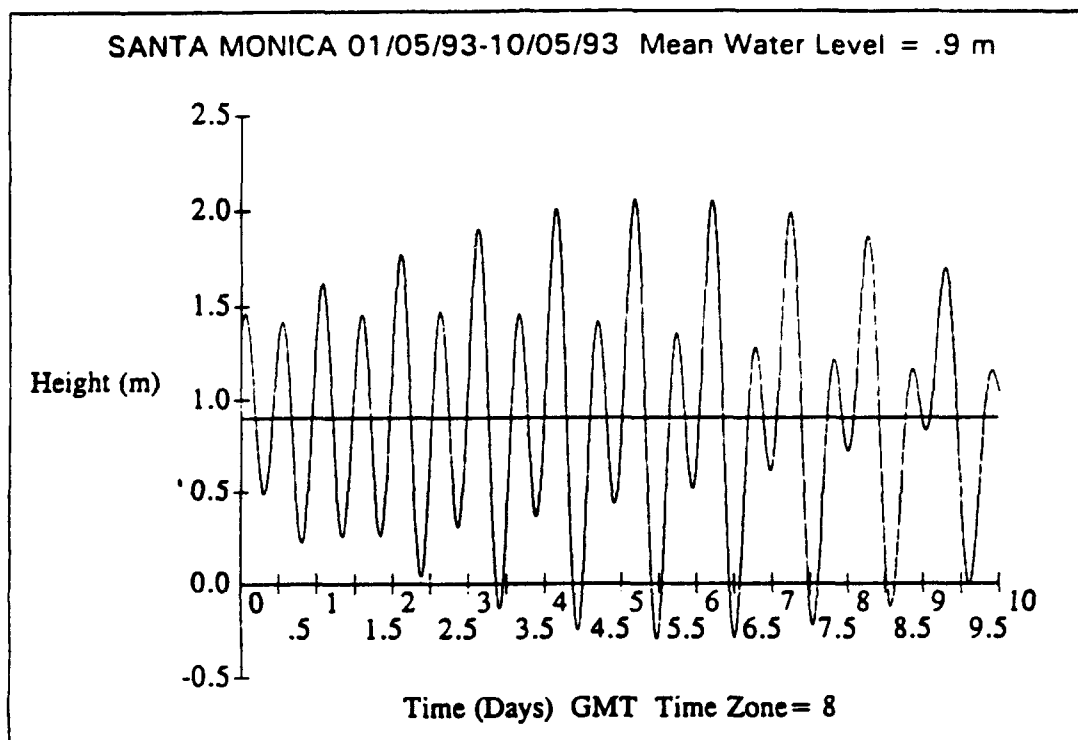


Fig. 5. Sample Tidal Height Plot at Santa Monica

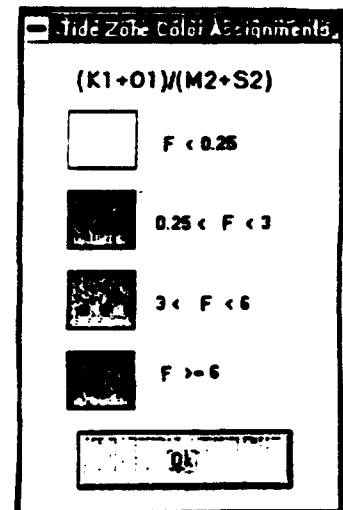


Fig. 6. Tidal Zone Plot of West Florida

IAS - Tidal Atlas Software [Untitled]									
Session	Data	View	Constituent	Image					
-43		
-44		
-45			Large river outflow and shallow banks						

-46		

-47		

Fig. 7. Example of GOT Data Flag off Argentina Coast

IV. Recommended Improvements

Many improvements can be implemented for TAS. The following is a recommended list:

1. Develop preprocessor features for coastal numerical models. Because of the importance of tides in the coastal processes, TAS can be very useful for coastal modeling studies. It provides not only tidal characteristics displays for model validation but also input information for modeling applications. However, it is time consuming to use bathymetry, coastline, and tide data for setting up the input files for a model. Features can be developed to automatically prepare input files for any area of interest. Because most of the modeling community are using Workstation/UNIX, it will be very useful to adopt the software to that environment.

2. Include additional databases in the software. Candidates include tidal current database of U.S. Coasts from National Ocean Service, Schwiderski's global M2 tidal current database, pelagic tidal constants compiled by Cartwright et al. (1979) and other global tide data from either model or altimeter data.

3. Add additional features. Many improvements can be made for the software. For instance, the following features can be added:

a. overlay two or more tidal curves,

b. plot bathymetry contours,

c. improve gridding and contours for phase data near 0° and 360° : At this moment, the contours near those values are not valid. The improvement can be accomplished by masking the area between 270° and 90° . Then the masked data are transformed into cosine or sine domain where the values are continuous. Finally, the gridded phase data are transformed back and merged with the rest of the data.

d. improve features for user imported data: Functions such as tagging and prediction can be added.

e. speed up the plotting of coastlines: The Mercator computation for each data point is very time consuming. It is possible to speed it up by using table look-up or some other techniques.

4. Conduct data quality checks for IHO data.

Typing errors were found in the IHO database. If the data is to be used for shipboard applications, data quality check needs to be performed.

V. Acknowledgments

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VI. References

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- Schwiderski, E.W. and L.T. Szeto, 1988. "The NSWC Global Ocean Tide Data Tape 18 (GOTD), Its Features and Application, Random-Point Tide Program," NSWC TR 81-254, 19 pp., Naval Surface Weapons Center, Dahlgren, VA.

APPENDIX A

**USERS MANUAL
FOR
TIDAL ATLAS SOFTWARE**

I. INSTALLATION

The compressed installation files are stored on a floppy disk. To install,

1. type win to start the Windows. If you have any other applications using an old version of threed.vbx file under the windows/system directory, you need to rename it. The vbx files are used by the Visual Basic for Windows applications.

2. insert the installation floppy.

3. click the Run button under the File menu, then type a:setup (or b:). TAS will be automatically de-compressed and installed. After the installation, a tidal atlas software window and icon appear.

4. double click the tidal atlas icon

A message indicates that the file TAS.INI is not properly set. One needs to establish the initial program setting.

5. Press Return, then enter the necessary information in the setup menu. A sample default setup is shown in Fig. A-1. Use Tab key to move to the next dialogue box.

A. In the Working paths, enter the desired paths.

- a. Main Directory - store main program and supporting routines
- b. Working Directory - store all user-created data files
- c. Temp Directory - store temporary files such as the combined IHO and GOT data before gridding.

B. In the Databases, enter the data paths

a. coastline

In the directory, it should contain the world vector shoreline file: lwvs.dat. The name is hard coded in the program. If the higher resolution file: 0wvs.dat needs to be used, one has to change its name to lwvs.dat.

b. bathymetry

It should contain the 5-minute etopo5.dat file.

c. GOT

It should contain i) Schwiderski's one degree resolution tide data got.dat, ii) Schwiderki's bad data flag files:schl_2.dos and sch2_2.dos.

d. IHO

It should contain iho.dat file and an index file iho.ndx. The file freq.tbl lists the tidal frequency and is used for converting between local and greenwich time for phase data.

C. Miscellaneous

a. Default Bathy Res:

Select one of the option buttons for desired resolution of bathymetry. The bathymetry file is used to create a mask for contouring. Otherwise, tidal contours will be plotted over land.

b. Default to Local Time

Session

Working Paths

Main Directory: c:\MasE Browse

Working Directory: c:\Mas3\work Browse

Temp Directory: c:\Mas3\temp Browse

☐ Clear-up temporary files on exit

Databases

Coastline: c:\database\coast Browse

Bathymetry: c:\database\batop5 Browse

GDT: c:\database\gdt Browse

H40: c:\database\h40 Browse

Miscellaneous

Default Bathy Res.

☒ 5 Minute

☐ 7.5 Minute

☐ 10 Minute

☐ Default to Local Time

Coastline Thinning: [X] []

Exit and Save Setup

Exit Only

Cancel

Fig. A-1. Dialog Box for Initial Setup

Click the check box for local time frame. The default time frame for IHO phase data is GMT.

c. Coastline Thinning:

Enter the desired thinning value, a value of 5 is recommended. The thinning is used to speed up plotting of coastlines. A value of 1 means using full resolution. For lwvs, it represents a resolution about 250 m.

6. After completing all dialogue boxes, click the Exit and Save button.

One is now ready to run the program by double clicking the TAS icon.

II. MENU INSTRUCTION

As shown in Fig. A-2, menu names are listed beneath the title bar, each menu item has several commands. The bottom status bar displays the retrieved file names and other selected parameters.

1. Session

A. New - start a new session.

B. Load - load an existing session, this will erase the present display and memory. Existing files in the working directory with *.ses extension are displayed as shown in Fig. A-3.

C. Save - save the present session. It is recommended to save the session after gridding function is performed since gridding is very time consuming.

D. Save as - save the present session under a different name

E. Print - print the present display

F. Printer Setup - the dialogue box is shown in Fig. A-4. One can select printer and picture orientation. Any new printer selection should be done under Windows (under control panel icon) before running the TAS. Further details can be found in the Windows manual.

G. Defaults - change initial program setup as described in the installation section

H. Exit - exit the program

2. Data

A. Area

a. User Defined - an example of the menu is shown in Fig. A-5. User needs to enter the coordinates of desired area. Longitude extends from -180 to 180 and latitude extends from -90 to 90. Therefore, West longitude and South latitude need to be entered as negative values. The name given in the default button will be used to name the retrieved data files.

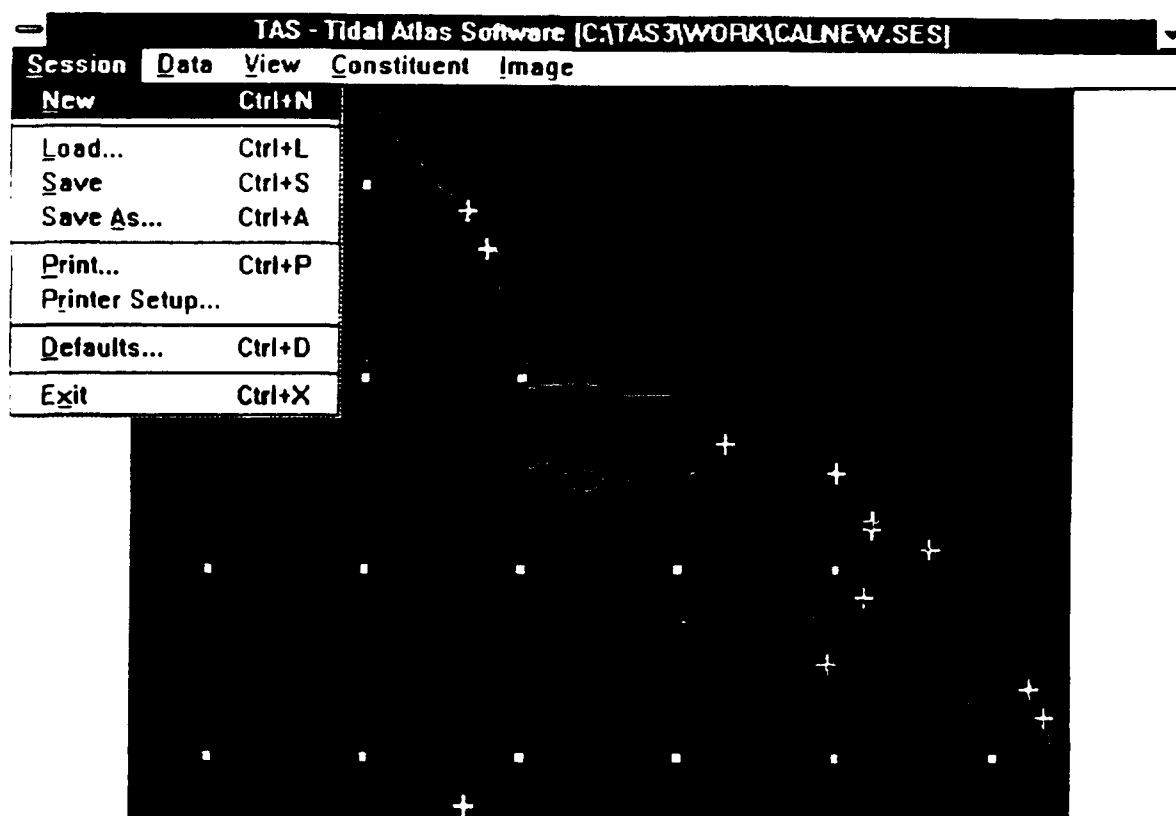


Fig. A-2. Function Menu

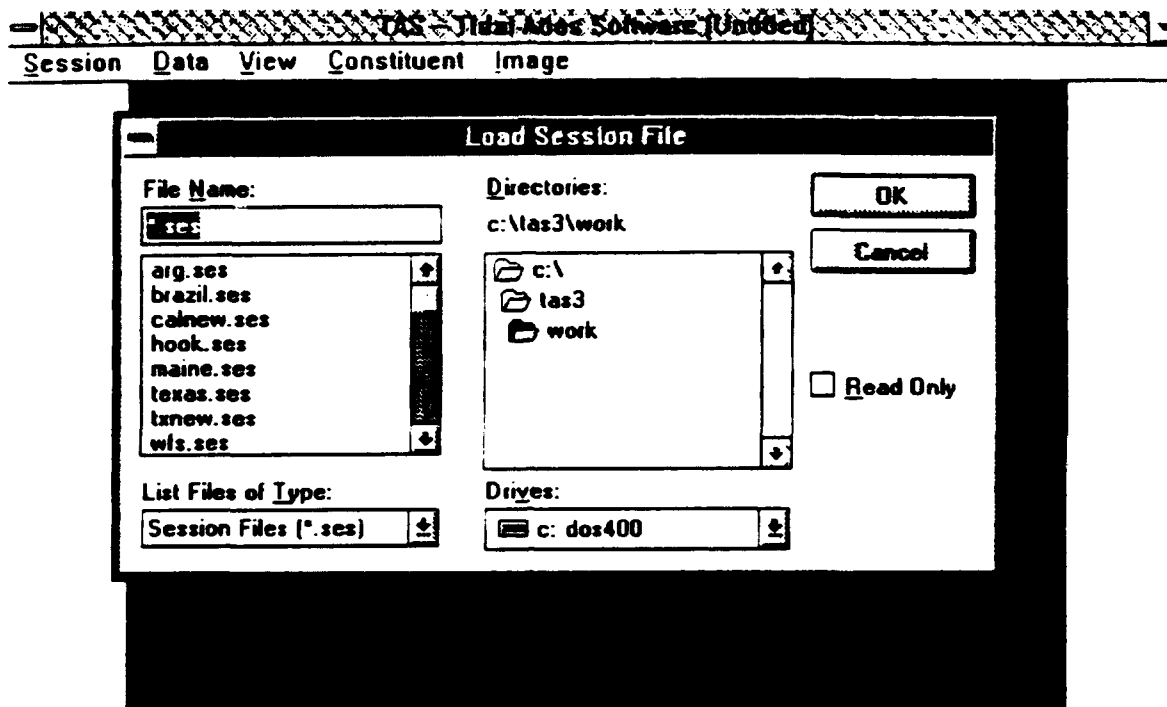


Fig. A-3. Dialog Box for Loading a Session

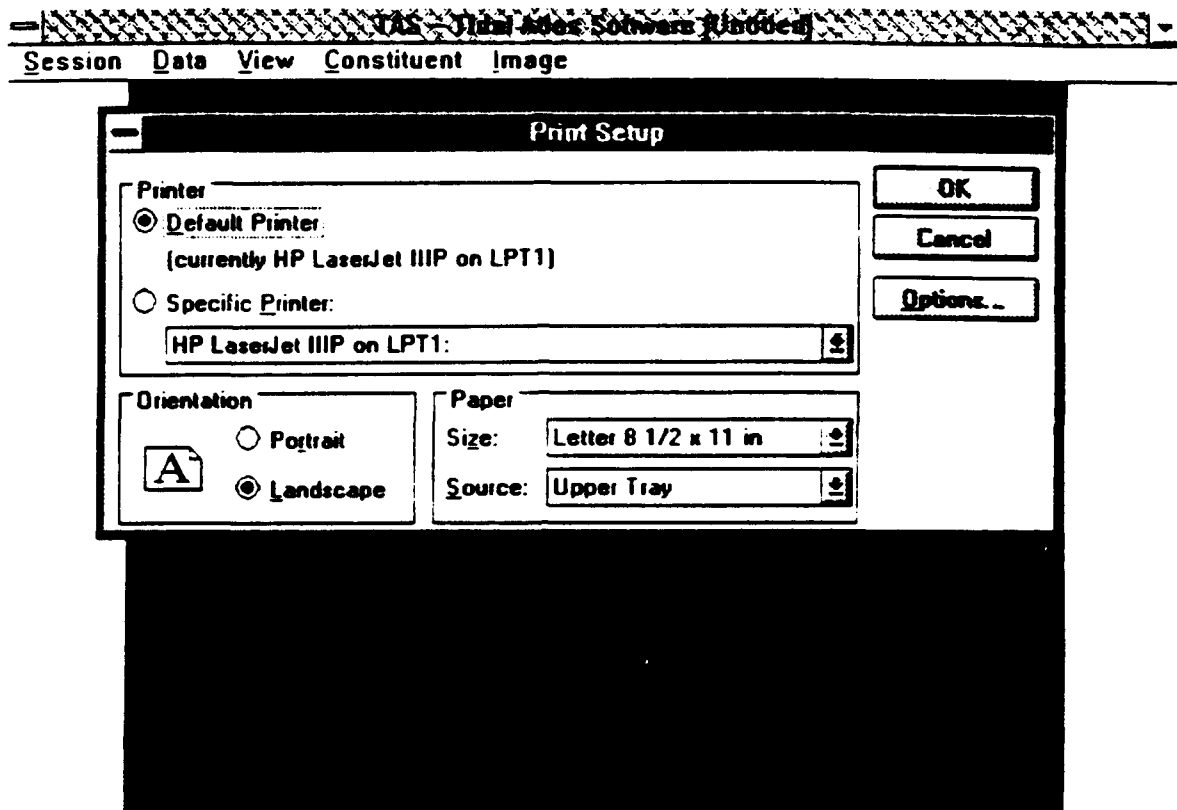


Fig. A-4. Dialog Box for Printer Setup

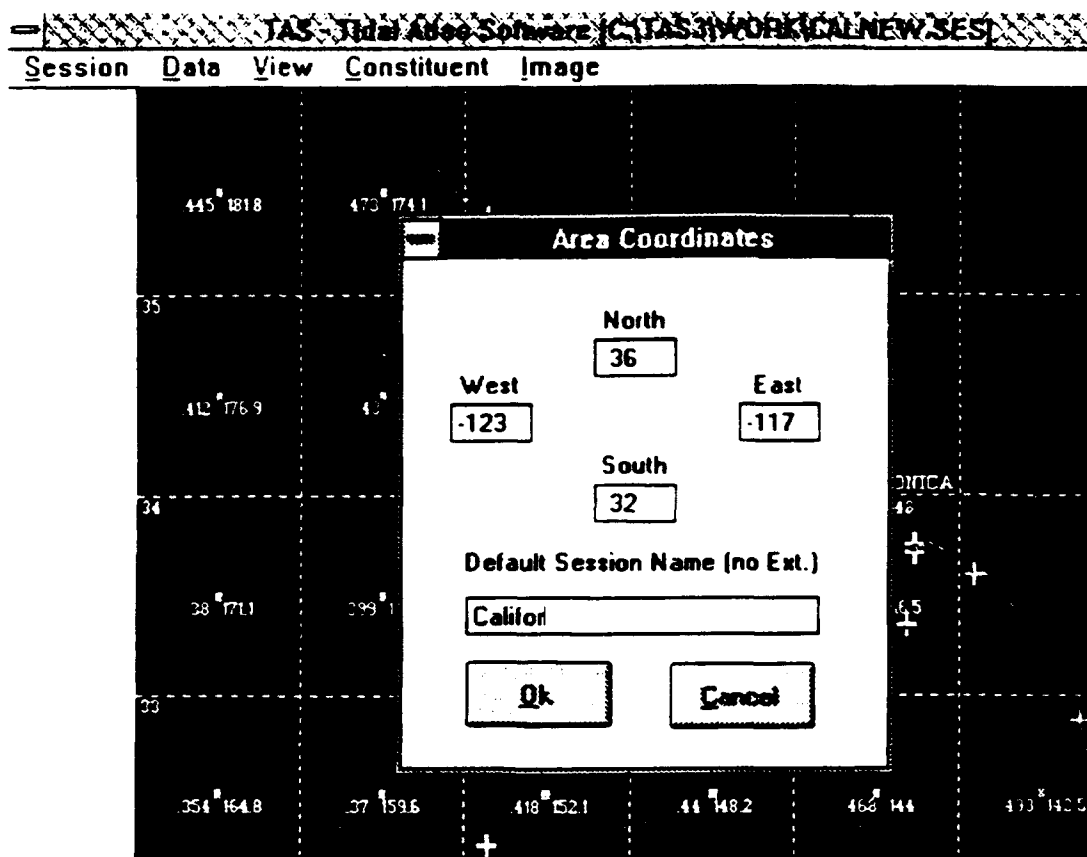


Fig. A-5. Dialog Box for Entering Area Coordinates

b. Zoom in 100% - zoom in the display to examine a crowded area. Depending the area size, one can usually zoom twice before running out of memory. Click the arrows on the border to move around.

c. Zoom out 100% - zoom out the display

B. Bathymetry

a. Load - load an existing bathymetry file with *.bth extension.

b. Retrieve - retrieve a new bathymetry file, change the file name if necessary.

c. Plot - only black and white overlay will be produced, the color feature is not implemented.

C. Coastline

a. Load - load an existing coastline file

b. Retrieve - retrieve a new coastline file. Coastlines are automatically plotted.

c. Toggle - The toggle function is used to take out the coastline display. It is useful during zooming operation to save time by avoiding plotting the coastlines. Coastlines can be re-plotted after proper zooming ratio and location are determined.

D. IHO

a. Load - load an existing IHO file

b. Retrieve - retrieve a new IHO file

c. Show Station - show the station marks

i) Show Selected - only tagged stations will be shown
Tagging function is performed by left mouse button.

ii) Show All - show all the stations

iii) Cancel

d. Tag Stations - show amplitude and phase for all IHO stations under the IHO station marks

Selected tagging can be performed by Shift+Left mouse key.

e. Station Color - select station color

E. GOT

a. Retrieve - retrieve a new GOT file

b. Show stations - show station marks

c. Tag stations - show amplitude and phase for all GOT stations

d. Show Flags - show schwiderski defined areas

e. Dump GOT Data to GOT.TAS - GOT data can be quickly retrieved, therefore it is usually not saved. This function allows saving the GOT data.

f. Station Color - select station color

F. User-defined

This function allows a user to enter additional data that need to be included in the gridding computation. Up to ten data points can be entered. An example is shown in Fig. A-6.

TAS - Tidal Atlas Software [C:\TASTEST\WORK\CAL8.SES]

Session Data View Constituent Image

TAS - Observed Data Input Worksheet

	Lat	Lon	M2	S2	K1	O1	N2	P1
Point 1 Ampl	-115.5	32.5	4	15				
Point 1 Phase			200	150				
Point 2 Ampl								
Point 2 Phase								
Point 3 Ampl								
Point 3 Phase								
Point 4 Ampl								
Point 4 Phase								
Point 5 Ampl								

Read USER.DAT Exit Only Exit and Save

Fig. A-6. Dialog Box for User-Imported Data

G. Grid

a. Amplitude and Phase - Current Const. - perform gridding to be used for plotting cotidal and corange charts for selected constituent

b. Amplitude and Phase - All const. - all eight major constituents will be gridded.

c. TideZone - gridding for tidal zone plot

3. View

A. Contours

a. Amplitude - plot corange chart

A dialogue box will appear for selecting desired constituent from a list of gridded constituents. A sample dialogue box for entering contouring information is shown in Fig. A-7.

b. Phase - plot cotidal chart

For both amplitude and phase contours, additional contours can be plotted by refreshing the display (see explanation in next section on Image menu)

c. Existing Contour File - retrieve and display existing contour files

d. Contour Color - select contour color

B. Tide Zones

a. Plot - plot the tide zone.

b. Tide Zone Color - the color bar for parameter F described earlier.

C. Sheet

a. Interpolate - interpolated amplitude and phase are produced for a defined sheet's center coordinates. An example of the sheet function is presented in Fig. A-8. The area defined is plotted as a box in the picture. The interpolated values are listed in the center of the box.

b. Random prediction - provide the tidal prediction for any user defined coordinate. The function can only be performed after all 8 major components are gridded.

D. Prediction

This function produces a tidal prediction curve. The time axis can be shown in either days or hours. For IHO data, a mean sea level is included in the plot. It is noted that for GOT points or any interpolated points as defined in Random Prediction operation, no attempt is made to show mean sea level.

E. Toolbar

This function generates a speed icon to reduce key strokes for some functions.

a. Predict - show prediction curve (for tidal prediction, see Sec. 7 on key and mouse functions)

b. IHO - load existing IHO files

Contour Information

Min: 35.4 cm Max: 54.9 cm

Minimum Contour: 35

Contour Interval: 5

Maximum Contour: 55

Labeling Options:

☒ Every contour

☐ Every other contour

Ok Cancel

Fig. A-7. Dialog Box for Contour Information

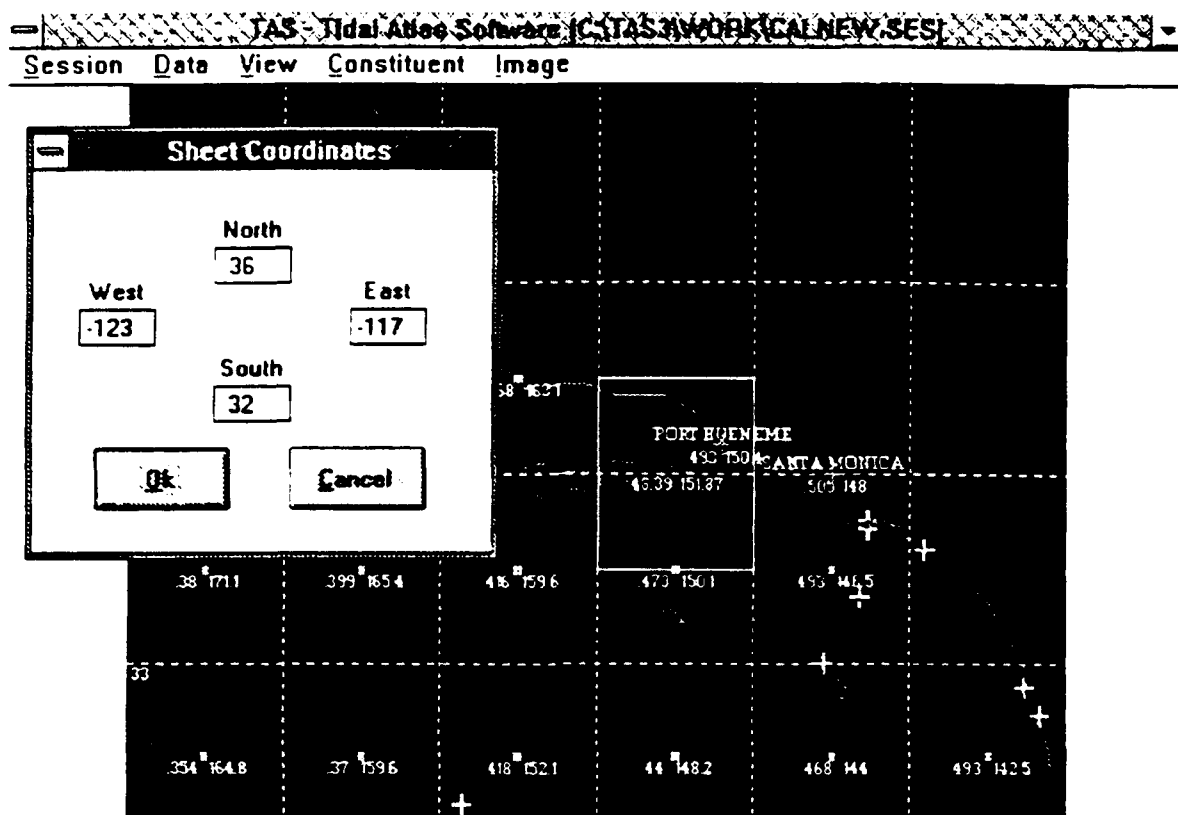


Fig. A-8. Example for Sheet Application

- c. GOT - retrieve GOT data
- d. SES - load saved sessions

All functions under the speedicon can be performed by using other menu items.

4. Constituent

For phase and amplitude data display, the default constituent is M2. Any major constituents (M2, S2, K1, O1, N2, P1, K2, and Q1) can be shown by clicking the desired constituent.

5. Image

- A. Toggle Coordinates - display or erase coordinates labels
- B. Toggle Grid - display or erase grid lines for longitude and latitude
- C. Refresh Display - Use to erase contour lines and tidal zone plot
- D. Background Color - select background color
- E. Foreground Color - select foreground color

6. Bottom Status Bar

- A. The first three fields show the file names for loaded or retrieved bathymetry, coastline and iho files.
- B. the fourth field - mouse position
- C. the fifth field - the status of job performed
- D. the sixth field - show time frame used, GMT or LCL (local)
- E. the seventh field - show the constituent selected
- F. the eighth field - show the area selected

7. Special Key and Mouse functions

LB- left mouse button
RB- right mouse button

A. Displaying tidal information - LB

This function displays the contents of IHO and GOT data files. An example of the tide data display has been shown in Fig. 2. Data listed in this window can be printed as listed in Table 1. It can also be printed in original IHO data format by clicking the button labeled Print Raw Data. A sample output is listed in Table 2. The IHO data format is included in the Table 3.

B. Tidal prediction - RB

This function performs the tidal height computation for a

specified duration. The time interval is hard coded as 15 minutes. A sample dialogue box for entering the dates is shown in Fig. A-9. To show the tidal curve, use the speed icon or the Prediction command under the menu item: View.

C. Tagging and un-tagging stations - Shift+LB

Under the station mark, this provides single tagging function for IHO and GOT data. This function is particularly useful for areas with many IHO stations.

D. Deleting and un-deleting stations - Ctrl+LB

Before the gridding, use this function to exclude any IHO and/or GOT data points under the station mark.

E. Switching from TAS to Program Manager of Windows - Alt+Tab

If speed icon is present, click the speed icon to go back to the current TAS session. Otherwise, use Alt+Tab or Ctrl+Esc to go back.

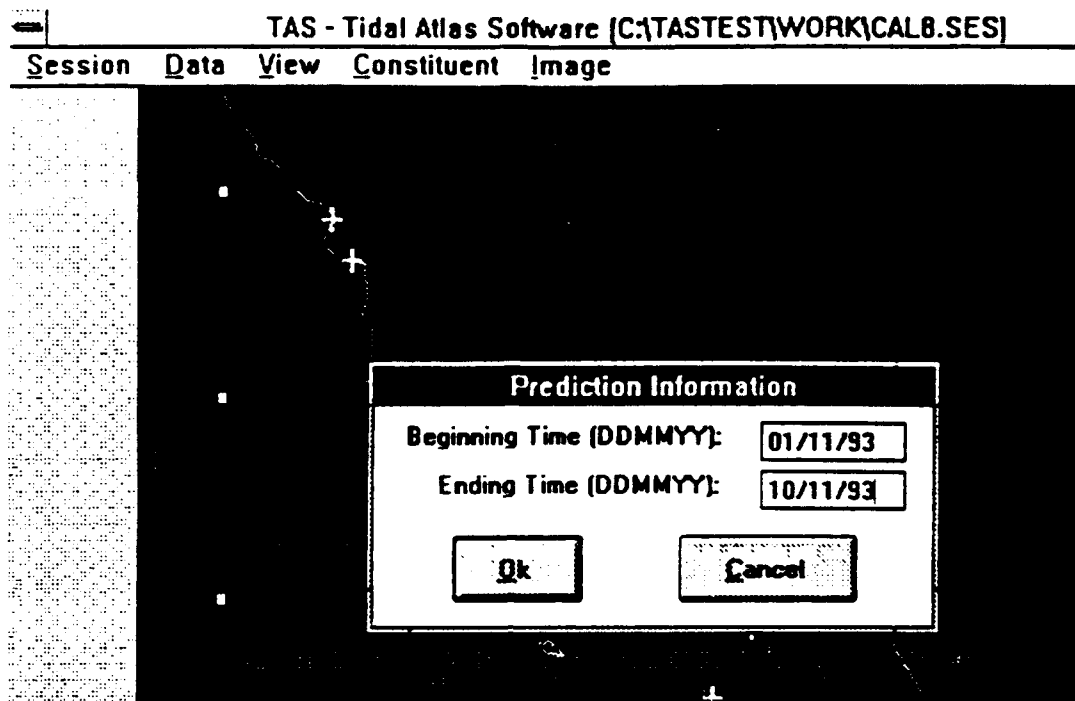


Fig. A-9. Dialog Box for Entering Dates of Tidal Prediction

IHO Station Name: SANTA MONICA
 Station Coordinates: -118.5 , 34.
 Number of Constituents: 9
 Time Zone: 8
 Mean Water Level: .9

K1	.341	88.2
O1	.215	83
P1	.11	85.8
Q1	.039	81.3
M2	.505	276.1
S2	.195	262
N2	.118	257.5
K2	.051	259.3
MU2	.017	221.3

Table A-1. Sample IHO Data

A2209	234001183001	2178	SANTA MONICA		
B2209		CALIFORNIA		N3400	W11830
C2209	31 57 06 99		8.000 D369 1919		
D2209	0.9 5144 USC		0 4	5	0 MT
F2209		K1		0.341	88.2
F2209		O1		0.215	83.0
F2209		P1		0.110	85.8
F2209		Q1		0.039	81.3
G2209		M2		0.505	276.1
G2209		S2		0.195	262.0
G2209		N2		0.118	257.5
G2209		K2		0.051	259.3
G2209		MU2		0.017	221.3

Table A-2. Sample IHO Data in Its Original Format

- 1) Record Length: 80 characters
- 2) Type of Record: 8 types of record identified by a letter from "A" to "H"
- 3) Common information for all types of records:
column 1: record type identification
columns 2-5: sequence number of station being retrieved
- 4) Record Type "A":
columns 14-25: station number
columns 31-35: S.P. 26 number
columns 41-80: station name
- 5) Record Type "B":
columns 16-55: location of the station
column 61: latitude designation N or S
columns 62-65: latitude number
 first two digits: number of degrees
 last two digits: number of minutes
column 75: longitude designation W or E
columns 76-80: longitude number
 first three digits: number of degrees
 last two digits: number of minutes
- 6) Record Type "C":
columns 14-15: country code
columns 20-25: sea code
columns 29-30: source code
columns 34-35: datum code
columns 39-45: time used in the analysis
columns 47-50: duration of the analysis
columns 52-60: period of the analysis
columns 66-72: height in meters
- 7) Record Type "D":
columns 11-15: mean in meters
columns 24-31: chart number
columns 44-48: number of Type "E" records to follow
columns 53-57: number of Type "F" records to follow
columns 62-66: number of Type "G" records to follow
columns 71-75: number of Type "H" records to follow
columns 79-80: unit of amplitude (MT = METERS, DB = DECIBARS)
- 8) Record Type "E": (all slow constituents)
columns 51-60: name of the constituent
columns 65-70: amplitude of the constituent in units specified in record type "D"
columns 76-80: phase lag of the constituent in degrees ("g")
- 9) Record Type "F": (all diurnal constituents) same as 8
- 10) Record Type "G": (all semi-diurnal constituents) same as 8
- 11) Record Type "H": (all over & compound constituents) same as 8

Table A-3. IHO Data Format

APPENDIX B Schwiderski's Report

ON ENHANCEMENT OF THE SCHWIDERSKI GLOBAL OCEAN TIDE MODEL

ERNST W. SCHWIDERSKI, CONSULTING INVESTIGATOR
102 BELL STREET
FREDERICKSBURG, VIRGINIA 22405
TELEPHONE (703) 371-4039

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SUMMARY

The present technical report on Enhancement of the Schwiderski Global Ocean Tide (SGOT) Model is prepared in consulting support of NOARL's Tide Program, consisting of two work tasks. The report reviews the accuracy of the consulting investigator's own SGOT model with particular attention to coastal waters, where the one-degree resolution naturally limits the model accuracy. In fulfillment of Task 1, three tables have been assembled, listing all coastal waters around the world, which need more detailed fine-scale tidal modeling. In fulfillment of Task 2, various suggestions and recommendations are presented based on the investigator's own extensive modeling experience enhanced by review and evaluation of the available literature.

1. INTRODUCTION

Since over a decade the Schwiderski (1978, 1980a,b and 1986) Global Ocean Tide (SGOT) model has been tested and proven its estimated realistic 10 cm accuracy in numerous applications ranging from oceanography down to geophysics of the solid earth and up to meteorology and space mechanics. In more recent years, the accuracy in the open oceans has been worldwide verified by analyses of GEOSAT altimeter measurements of the sea surface topography, such as by Cartwright and Ray (1990). This excellent accuracy is only slightly less in regions adjacent to large archipelagos, shallow banks and large river outflows (Table 3). The SGOT model consists of four semidiurnal (M2,S2,N2,K2), four diurnal (K1,O1,P1,Q1) and three long-period (Mf,Mm,Ssa) components (Schwiderski 1979 and 1981 and Schwiderski and Szeto 1981), which may be supplemented by several interpolated minor partial tides. In the open oceans each component is hydrodynamically computed and tabulated by their harmonic constants (amplitudes and phases) on a one-degree grid system. Both constants are representative tidal averages within the one-degree grid areas including coastal grid cells. However, in general only in deep-ocean grid cells it is justified to consider the average cell data as close approximations of real constants at the centers of the grid areas. The close relationship is due to the negligible lateral variation of deep-ocean tides over large areas compared to the grid area.

In contrast, due to local basin conditions, such as rough shorelines and shallow bottom reliefs, coastal tides may vary rapidly over short lateral distances. Hence, the one-degree resolution of the SGOT model is naturally insufficient to allow the desired approximation of point tide data by averaged area data in many coastal waters. In fact, the applied hydrodynamical interpolation of averaged empirical tide data along shorelines avoided the problem of realistically resolving coastal tides pointwise as needed in most applications. The detailed resolution of coastal tides has been the subject of numerous local coastal models, which have been developed with more or less success during the past two decades. Among the more successful results it is useful to point out the models around the British Isles by Flather (1976), Prandle (1980) and Gray et al. (1987) and of the Gulf of Mexico by Reid and Whitaker (1981).

Much work remains to be done to generate accurate and practically useful tide models in coastal waters. It is one objective of NOARL's Tide Program, which is funded by CNO/OP-096. The present technical report is prepared in consulting support of the program. The following Section 2 deals with Task 1, listing all coastal waters of the world oceans, which are insufficiently resolved in the SGOT model. Section 3 deals with Task 2, listing some technical suggestions and recommendations to enhance the tidal resolution in the areas listed in Section 2.

2. COASTAL WATERS OF THE WORLD OCEANS INSUFFICIENTLY RESOLVED IN THE SGOT MODEL

In the following TABLES 1, 2, and 3 all coastal waters of the world oceans are listed, which are insufficiently resolved in the one-degree SGOT model. The three tables are assembled by the particular geographical features of the listed areas.

In TABLE 1, all ocean bays, border seas and straits are listed in apparent geographical order around the world. Areas with no modeled tide data (e.g. Hudson Bay or Mediterranean Sea) are marked by (a). In the SGOT model they were considered as disjoint from the global ocean basin within one degree. Regions with only averaged empirical tide data (e.g. Florida Strait or English Channel) are marked by (b). Finally, areas with insufficiently resolved tide data (e.g. Baffin Bay or Gulf of Mexico) are marked by (c). Regional tide models of those coastal waters require some knowledge of realistic tide data along the geographically obvious open ocean connection (Section 3).

In TABLE 2, all open ocean archipelagos and island chains (such as Iceland or Bahama Islands) are listed in geographical order. As explained in Schwiderski (1978, 1979 and 1980a,b) such large obstacles cause large distortions and retardations of tidal waves passing or crossing the areas from one side to the other. The detailed resolution of these effects requires regional fine-scale models with open ocean boundaries all around the areas.

Finally, in TABLE 3, all shallow open ocean coastal waters (such as, Grand Banks or Amazon River area) are listed in geographical order. In these areas large tidal effects are caused by shallow sand banks, archipelagos and/or large river outflows. For fine-scale modeling of the tidal effects the area boundaries are given from shore points to shore points with specified geographical coordinates on the open ocean side.

TABLE 1. Ocean Bays, Border Seas and Straits (a. No modeled tide data b. Averaged empirical tide data c. Insufficient resolution)

WEST ATLANTIC OCEAN:

North America:

- Baffin Bay (c)
- Hudson Bay (a)
- Davis Strait (c)
- Gulf of St Lawrence (c)
- Bay of Fundy (a)
- Long Island Sound (a)
- Delaware Bay (a)
- Chesapeake Bay (a)
- Florida Strait (b)

South America:

- Gulf of Mexico (c)
- Caribbean Sea (c)
- Drake Passage (c)

EAST ATLANTIC OCEAN:

Europe:

- Denmark Strait (c)
- Iceland - Faeroe Gap (c)
- Baltic Sea (a)
- North Sea (c)
- English Channel (b)
- Irish Sea (a)
- Mediterranean Sea (a)

Africa:

- Gulf of Guinea (c)

WEST INDIAN OCEAN:

Africa:

- Red Sea (a)
- Gulf of Aden (c)
- Mozambique Channel (c)

NORTH INDIAN OCEAN:

Asia:

- Gulf of Oman (c)
- Persian Gulf (a)
- Gulf of Mannar (b)
- Bay of Bengal (c)

EAST INDIAN OCEAN:

Asia:

- Andaman Sea (c)
- Malacca Strait (c)

Australia:

- Timor Sea (c)
- Arafura Sea (c)
- Gulf of Carpentaria (c)
- Bass Strait (b)

WEST PACIFIC OCEAN:

Asia:

- Bering Sea (c)
- Gulf of Anadyr (c)
- Gulf of Olyufor (c)
- Okhotsk Sea (c)
- Japan Sea (a)
- Gulf of Chihli (a)
- Yellow Sea (c)
- East China Sea (c)
- Formosa Strait (b)
- Gulf of Tonkin (c)
- Gulf of Siam (b)

Southeast Asia:

- South China Sea (c)
- Java Sea (b)
- Sulu Sea (b)
- Celebes Sea (b)
- Makassar Sea (b)
- Flores Sea (b)
- Savu Sea (b)
- Ceram Sea (b)
- Banda Sea (b)
- Molucca Sea (b)
- Gulf of Papua (c)
- Bismarck Sea (c)
- Solomon Sea (c)

Australia:

- Torres Strait (b)
- Coral Sea/Reef (a)

New Zealand:

- Bay of Plenty (c)
- Cook Strait (b)
- Half-Moon Bay (a)

EAST PACIFIC OCEAN:

North America:

- Bering Strait (b)
- Bristol Bay (b)
- Gulf of Alaska (c)
- Hecate Strait (b)
- Juan de Fuca Strait (b)
- San Francisco Bay (a)
- San Diego Bay (a)
- Gulf of California (a)

South America:

- Gulf of Panama (c)

ARCTIC OCEAN:

North America:

- Chukchi Sea (c)
- Beaufort Sea (c)

Europe:

- Barents Sea (c)

Asia:

- Kara Sea (c)
- Laptev Sea (c)
- East Siberian Sea (c)

Antarctic Coast:

- Weddel Sea (c)
- Ross Sea (b)
- Amundsen Sea (c)
- Bellingshausen Sea (c)

TABLE 2. Ocean Archipelagoes and Island Chains with large tide distortions and retardations (area coordinates should be chosen to best suit the modeling specifics)

ATLANTIC OCEAN:

North:

- Iceland
- Faeroe Islands
- Shetland Islands
- Azore Islands
- Madeira Islands
- Canary Islands
- Cape Verde Islands
- Bahama Islands
- Antilles

South:

- Falkland Islands
- South Georgia Islands
- South Sandwich Islands
- South Orkney Islands
- South Shetland Islands
- Tristan da Cunha Islands

INDIAN OCEAN:

West:

- Laccadive Islands
- Maldiv Islands
- Chagos Islands
- Seychelles Islands
- Mascarene Islands
- Prince Edward Islands
- Crozet Islands
- Kerguelen Islands

East:

- Andaman Islands
- Nicobar Islands

PACIFIC OCEAN:

North:

- Aleutian Islands
- Kuril Islands
- Hawaiian Islands
- Marshall Islands
- Nampo Shoto Islands
- Ryukyu Islands
- Mariana Islands
- Caroline Islands
- Philippine Islands

South West:

- Bismark Archipelago
- Solomon Islands
- New Hebrides Islands
- New Caledonia Islands
- Gilbert Islands
- Ellice Islands
- Fiji Islands

South East:

- Line Islands
- Phoenix Islands
- Samoa Islands
- Tonga Islands
- Kermadec Islands
- Cook Islands
- Tubuai Islands
- Society Islands
- Tuamotu Archipelago
- Marquesas Islands
- Eastern Islands
- Galapagos Islands

ARCTIC OCEAN:

- Queen Elizabeth Islands
- Spitzbergen Islands
- Franz Josef Land Islands
- North Land Islands
- New Siberian Islands

TABLE 3. Shallow Open Coastal Waters (Effectuated by Shallow Banks, Archipelagos and Large River Outflows)

ATLANTIC OCEAN:

Grand Banks: From Cape Bauld, New Foundland to (48N,43W) - (43N,50W) to Halifax, Nova Scotia.

Delaware/Chesapeake Bay Area: From Atlantic City to (39N,72W) - (34N,74W) to Cape Hatteras.

Amazon River Area: From Paramaribo, Surinam to (8N,54W) - (0N,41W) to Paranaiba, Brazil.

Rio de La Plata Area/Patagonian Shelf: From Rocha, Uruguay to (35S,50W) - to Staten Island, Argentina.

Southeast Greenland Coast: From Kap Karvel to (58N,44W) - (66N,31W) to Kap Gustav Holm.

Northeast Greenland Coast: From Kap Parry to (70N,12W) - (10N,1W) to Nordost Rundingen.

Norway Coast: From Nord Kapp to (72N - 19E) - (63N,1E) to Flora.

Strait of Gibraltar Area: From Lisbon, Portugal to (40N,12W) - (33N,13W) to Safi, Morocco.

Senegal River Area: From Cap Blanc, Mauritania to (21N,20W) - (10N,19W) to Cap Verga, Guinea.

Congo River Area: From Nyanga, Gabon to (3S,7E) - (13S,10E) to Lobito, Angola.

Agulhas Bank: From Cape of Good Hope to (38S,18E) - (38S,26E) to Port Elizabeth, South Africa.

INDIAN OCEAN:

Indus River Area: From Gwadar, Pakistan to (23N,63E) - (15N,72E) to Panjim, Goa.

Northwest Australia: From Cape Talbot to (12S,125E) - (20S,112E) to Northwest Cape.

Southern Australia: From Cape Pasley to (35S,124E) - (39S,139E) to Mount Gambier.

PACIFIC OCEAN:

Kamchatka Coast: From Mys Lopatka to (51N,158E) - (56N,165E) to Mys Sivuchiy.

Alexander/Queen Charlotte Islands: From Yakutat, Alaska to (58N,143W) - (50N,130W) to Cape Scott, Vancouver Island.

Ecuador Coast: From Buenaventura, Colombia to (5N,83W) - (8S,82W) to Trujillo, Peru.

Coast of Chile: From Valparaiso to (33S,75W) - (57S,75W) to Cape Horn.

3. ON FINE- SCALE MODELING OF COASTAL WATER TIDES

The fine-scale modeling of tides in coastal waters has attracted considerable attention of many oceanographers for more than two decades. Due to the great hydrodynamical complexity of the problem various methods have been developed and tested with more or less success. Considering the large number of coastal waters in need of improved tidal knowledge (TABLES 1,2 and 3) only very few areas have been considered in the past. Much more work is needed to develop simple and efficient techniques. Indeed, most of the highly sophisticated available methods are difficult to implement in the needed massive practical applications.

During the contract period numerous technical papers on modeling of coastal water tides (such as listed in the REFERENCES) have been reviewed and evaluated for their usefulness. Based on these studies and on the investigator's own extensive modeling experience, the following major problems and suggestions for their solution may be pointed out:

3.1. Open Ocean Boundary Data:

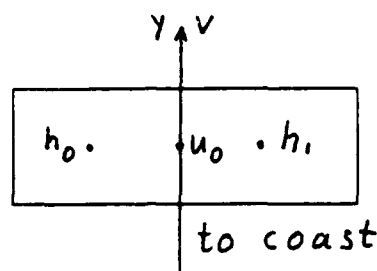
The need of realistic boundary data along the open ocean side remains as one of the most important problems. Since the gravitational forces of the moon and sun are almost ineffective in shallow waters, coastal water tides are mainly driven by the global deep-ocean tides. Realizing that it is not sufficient to prescribe only tidal elevations along the open ocean boundary line (line conditions) most researchers such as Miller and Thorpe (1981), Reid and Whitaker (1981), Raymond and Kuo (1984), Blumberg and Kantha (1985), Roed and Cooper (1986) and Hedley and Yau (1988), considered radiation conditions with unspecified parameters requiring involved tuning procedures. To simplify such time-consuming trial and error procedures, it is suggested to replace the classical line conditions by tidal strip conditions to define tidal velocities tangentially and normally to the boundary line. These velocity components may be modified by simple perturbation parameters simulating radiation conditions, for example.

In more detail, consider the linear momentum equations

$$u_t + bu - fv = a(g_x - h_x)$$

$$fu + v_t + bv = a(g_y - h_y)$$

at the open boundary point (u_0) in the figure below. Let, in complex notation



$$u = Ue^{i(t\sigma - \alpha)}, g = Ge^{i(t\sigma - \gamma)},$$

$$v = Ve^{i(t\sigma - \beta)}, h = He^{i(t\sigma - \delta)},$$

then

$$(b + i\sigma)Ue^{-i\alpha} - fVe^{-i\beta} = A,$$

$$fUe^{-i\alpha} + (b + i\sigma)Ve^{-i\beta} = B,$$

where

$$A = a(G_x - i\gamma_x G)e^{-i\gamma} - a(H_x - i\delta_x H)e^{-i\delta},$$

$$B = a(G_y - i\gamma_y G)e^{-i\gamma} - a(H_y - i\delta_y H)e^{-i\delta}.$$

With given tidal strip conditions, i.e. h_0 and h_1 , known, $H, H_x, H_y, \delta, \delta_x$ and δ_y are determined at the boundary point (u_0) as averages and/or finite differences. Hence, (U_0, α_0) and (V_0, β_0) are known and can be used to control the normal and tangential flow in the coastal region. It may be mentioned, that with u and h known at the boundary point (u_0) the unknown constant c in the classical radiation condition (Reid and Whitaker (1981), Eq. 10c)

$$u - ch = g$$

can be determined without trial and error computations.

3.2. Shoreline Modeling:

To model the complicated shorelines more accurately, it is suggested to use more realistic tangential lines instead of the usually used grid lines (some ideas are considered in Schwiderski 1978 and 1980a and b).

3.3. Turbulent Friction Modeling:

To model the turbulent friction of the tidal flow, parameterized linear and/or nonlinear friction terms are recommended.

3.4. Nonlinear Hydrodynamical Equations:

In regions of large tidal velocities such as the Bay of Fundy or the Patagonian Shelf, the tidal equations should be augmented by nonlinear friction, inertial, and continuity terms. The latter terms are particularly important in shallow coastal waters with dry periods.

3.5. Tidal Loading

In many areas yielding of the solid earth due to tidal loading may be significant and should be investigated.

3.6. Initial Approximations

The use of SGOT data augmented by available empirical tide data (such as from the British Admiralty Tide Tables, the International Hydrographic Bureau and the IAPSO Publications of Cartwright and Zetler 1979 and 1985) is recommended instead of the customary zero initial approximations. A speedup in convergence of the time-stepping numerical integration can be expected.

3.7. Negative Averaging

To improve the convergence of the numerical procedure negative averaging over half tidal periods is recommended during appropriate time steps (Schwiderski 1981, TR 82-151).

3.8. Interpolation of Empirical Tide Data:

Considering the complexity of the turbulent tidal motions in coastal waters, it is highly recommended, to develop new techniques to interpolate accurate empirical tide data along and off shorelines into the model. The interpolation may be accomplished by hydrodynamical interpolation such as used by Schwiderski (1978 and 1980a,b), i.e. by tuning of boundary and friction parameters during the numerical integration. Finally, the integrated model may be further fitted to empirical tide data by least squares methods applied to appropriate perturbation parameters. For example, two tidal states may be averaged with appropriate weights to match empirical tide data (generalized negative averaging, 3.7 above).

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